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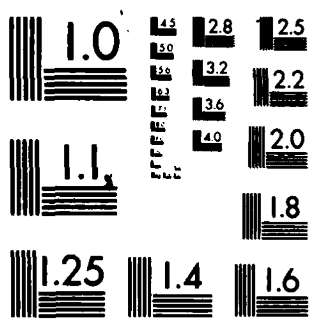

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The Defense Mapping Agency, in cooperation with the United States Geological Survey and the National Oceanic and Atmospheric Administration, is sponsoring the development of a Global Positioning System geodetic receiver (GEOSTAR). The receiver is capable of observing up to four satellites simultaneously by sampling segments of broadcast signals from different satellites in a time-multiplexing sense using a single dual frequency channel. The receiver system was designed to measure the geodetic coordinates of points to an accuracy of one meter and to provide first-order estimates of baselines of up to several hundred kilometers in length. In addition, the receiver can support positioning and attitude determination of geophysical survey platforms under low dynamic conditions. Descriptions of these applications are presented.

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APPLICATIONS OF THE GPS GEODETIC RECEIVER SYSTEM

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ABSTRACT

The Defense Mapping Agency, in cooperation with the United States Geological Survey and the National Oceanic and Atmospheric Administration, is sponsoring the development of a Global Positioning System geodetic receiver. The receiver is capable of observing up to four satellites simultaneously by sampling segments of broadcast signals from different satellites in a time-multiplexing sense using a single dual frequency channel. The receiver system was designed to measure the geodetic coordinates of points to an accuracy of one meter and to provide first-order estimates of baselines of up to several hundred kilometers in length. In addition, the receiver can support positioning and attitude determination of geophysical survey platforms under low dynamic conditions. Descriptions of these applications are presented.

1. INTRODUCTION

The geodetic community has used the Navy Navigation Satellite System (TRANSIT) to determine the position of thousands of sites since 1963. Doppler measurements, typically thirty to thirty-five passes, are processed to provide positional accuracy of about one meter.

Soon after conceptual development of the GPS by the Department of Defense, proposals were made by a number of investigators for the application of GPS to geodetic problems. Simulations indicated that a multiple channel GPS receiver could achieve geodetic accuracy after only a few hours on station. Early concepts for GPS geodetic receivers usually involved the application of a navigation receiver. These concepts, as they matured, produced conflicts between requirements for navigation and for geodetic positioning that led to the decision to develop a GPS receiver system designed and tailored to meet geodetic requirements. The Defense Mapping Agency, in cooperation with the U.S. Geological Survey (USGS) and the National Oceanic and Atmospheric Administration (NOAA), is sponsoring the development of a NAVSTAR Global Positioning System (GPS) geodetic receiver to meet such requirements.

This paper will discuss several unique GPS applications of this receiver.

2. THE NAVSTAR GLOBAL POSITIONING SYSTEM

The NAVSTAR Global Positioning System is a satellite-based navigation system designed to provide continuous all-weather navigation to appropriately equipped users on a worldwide basis (Payne, 1982). The operational system, scheduled for the late 1980s, will consist of 18 satellites in circular orbits having 55-degree inclinations and orbit periods of about 12 hours (Figure 1). This constellation geometry provides the visibility of four to seven satellites anywhere in real-time. Each satellite carries an atomic clock with long-term stability of a few parts in 10^{12}. Navigation signals consisting of spread spectrum, pseudorandom noise (PRN) signals on two coherent L-band frequencies are transmitted continuously. The conventional receiver decodes the PRN signal to obtain orbital elements, time calibration data, and measurement data.

3. GPS GEODETIC RECEIVER SYSTEM

The applications discussed in this paper make use of the hardware and software properties of the GPS geodetic receiver system. The receiver consists of a single RF/IF channel that continuously, in a time-multiplexing sense, tracks four satellites. Figure 2 shows the multiplexing sampling and its relationship to the received signals. Each satellite is assigned a software tracker that samples code and carrier information from both L1 (1575.42 MHz) and L2 (1227.6 MHz). The samples are used to update code and carrier software tracking loops which ultimately provide pseudorange and phase observations (Ward, 1982). Figure 3 is a simplified system block diagram illustrating the internal segments and provisions for peripherals.

Physically the receiver weighs 50 pounds, is battery operated, and is intended to be a rugged field-portable system. It is composed of an antenna/preamplifier, connecting cables, a receiver section, receiver processor, navigation processor, and peripherals. The antenna/preamplifier is a nine-inch high cone sitting on top of a two-inch high preamplifier housing that can be located up to 100 feet from the receiver. The receiver and navigation processor are in the same 15 by 17 by 8-inch housing. A control display unit attached to a six-foot cable is a part of the receiver/navigation processor. Figure 4 shows a typical geodetic setup of the receiver. Normally, a dual cassette recorder is used. For several of the following applications, however, the data recording will be handled by a different data storage system.

The receiver can be thought of as a software machine since most of the receiver functions are handled by the receiver processor, a SBP 9990 microprocessor, with RAM making up 75 percent of the memory. A second SBP 9990 is employed to perform geodetic solutions in real-time by communicating, through shared memory, with the receiver processor. The system's flexibility, offered by this dual microprocessor RAM memory arrangement, makes the receiver an ideal system for various applications of the Global Positioning System.

4. APPLICATIONS

The geodetic receiver was developed for stationary, absolute, and relative positioning applications. The receiver can, however, be used with various low dynamic geophysical survey platforms. The sections that follow will describe some of these applications in more detail.

4.1 Geodetic Positioning

The primary application which led to the development of the GPS geodetic receiver system is geodetic positioning analogous to dynamic point positioning currently performed using the Transit system (Smith, et al., 1976). In this application, either range or integrated Doppler (phase accumulation) observations using both L1 and L2 are obtained from four satellites simultaneously during a site occupation of less than one day. Two frequency observations are used to eliminate first-order ionospheric refraction. The particular satellites used during the occupation period will vary among those available based on a serial optimization of the site coordinate estimation. Additional parameters for receiver frequency error and anomalous tropospheric refraction are included in the estimation as required. Precise GPS satellite ephemerides will provide satellite positions necessary in the post mission data processing algorithms. Real-time position estimation using the broadcast GPS navigation message will be performed for on-site quality assurance.

Detailed simulations of geodetic positioning using range and Doppler observations from a single channel receiver for a GPS-type constellation have inferred positional accuracies of a meter after 24 hours of continuous observation (Fell, 1980). Observational noise levels similar or larger than those obtainable with the geodetic receiver were assumed. Errors in satellite ephemerides, satellite and receiver atomic oscillators, and tropospheric refraction were considered. Since the receiver, in a time-multiplexing sense, tracks four satellites simultaneously, the received satellite geometry will be optimized faster than those assumed in simulation. It is thus anticipated that one meter accuracy in each coordinate of position may be obtained in six to twelve hours, or possibly in less time, if elements of the simulation error budget (Fell,1976) are improved in actual applications.

The capability to perform accurate geodetic positioning worldwide using GPS observations will provide for continuing support to those elements of mapping, charting, and geodetic applications currently supported by Transit satellite positioning. These include the accurate positioning of instrumentation, control for national or regional survey networks, the development of satellite derived regional geoids, control for photogrammetric mapping, and development of datum transformations.

4.2 Static Baseline Determination

A second geodetic application for the GPS geodetic receiver system, the one of high priority to the National Geodetic Survey of NOAA, is the estimation of precise baselines between fixed points. Accomplishment of first-order accuracy within a few hours of site occupation is the goal of this development.

The approach to this problem is to simultaneously measure the phase of the two reconstructed GPS carrier frequencies, L1 and L2, from each of four satellites simultaneously at two or more sites separated by up to hundreds of kilometers. Again, observations are made on two coherent frequencies to eliminate first-order ionospheric refraction effects. The phase observations obtained may be treated in one of several ways prior to baseline estimation. Such approaches consist of taking single or double differences of phase observation to eliminate particular error sources or model parameters required using nondifferenced observations (Fell, 1980) (see Section 4.4 for additional details).

Simulations of baseline determination using a single channel receiver with double-differenced phase measurements indicate that first-order accuracy can be achieved for 100-kilometer baselines in about six hours. The use of simultaneous phase measurements to four satellites will provide such accuracy in approximately two hours. This level of accuracy has already been demonstrated using the Macrometer (Goad and Remondi, 1983) which adopts a different measurement procedure on only one frequency, but uses a similar data processing approach.

The geodetic and geophysical applications of precise baseline determination include survey densification, monitoring of crustal motion, and transferring local control across areas where conventional survey methods are not applicable.

4.3 Dynamic Relative Positioning

Dynamic relative positioning has been proposed as a means whereby scientific survey ships operating in coastal waters may achieve accurate tracks of position with respect to time. Data would be recorded simultaneously on the ship and at one or more fixed sites on land. After the operations are completed, the data sets would be processed to obtain the desired information. An accuracy goal of less than 5 meters error in a three-dimensional position fix has been proposed.

Figure 5 illustrates the receiver and satellite relationships. Biased range data are recorded by each receiver from the four satellites. The bias represents the combination of local time error t_i and satellite time error T_j. The observation is therefore:

$$R_{ij} = r_{ij} + t_i + T_j \qquad (1)$$

where i represents the receiver, j represents the satellite, and r_{ij} is the geometric range from site i to satellite j.

In order to eliminate the time errors, the biased ranges are differenced twice. The first difference is performed on the observations at each receiver. One of the satellite observations is subtracted from the other three. This eliminates the receiver contribution t_i and other propagation errors that are common to both transmission paths and have a form similar to a bias.

$$R_{ij} - R_{in} = r_{ij} + t_i + T_j - r_{in} - t_i - T_n$$

$$R_{ij} - R_{in} = r_{ij} - r_{in} + T_j - T_n \quad . \qquad (2)$$

The second difference is performed between observations of a single satellite recorded by both receivers. This removes satellite timing errors and other errors, such as radial orbit error, that have a similar form:

$$R_{ij} - R_{in} - (R_{mj} - R_{mn}) = r_{ij} - r_{in} + T_j - T_n - (r_{mj} - r_{mn} + T_j - T_n)$$

$$R_{ij} - R_{in} - R_{mj} + R_{mn} = r_{ij} - r_{mj} - (r_{in} - r_{mn}). \qquad (3)$$

The resulting quantity contains multiple differences of ranges between satellites j and n and receivers i and m. It is no particular advantage to locate the fixed sites near dynamic sites. All that is required is that they observe the same satellites over a substantial period of time.

This doubly differenced data can then be used to solve for the dynamic receiver position relative to the stationary sites. It is expected that sufficient data will be accumulated during the planned field tests to evaluate various techniques and geometric arrangements of receivers. The intent is to have one or more fixed receivers and one to several dynamic receivers. The data collected will be both pseudorange and accumulated Doppler phases along with the broadcast ephemeris and other support data. The strength of these solutions will be compared to solutions calculated using standard differencing procedures.

4.4 Attitude Determination

Prior to th. development of the NAVSTAR Global Positioning System, only inertial measurement systems had the potential to provide both position and platform orientation, 6 degree-of-freedom information, as a stand-alone system (Johnson, et al., 1981-82). Now, GPS receivers have been successfully used to determine antenna position (Henderson and Strada, 1980; Lachapelle, et al., 1982; and O'Toole and Carr, 1982). Also, a number of proposals have been made to use phase measurements from multiple GPS satellite tracking receivers to determine platform orientation (Johnson, et al., 1981-82; Ellis and Greswell, 1979; and Griffin and Coulbourn, in press). These proposals adopt interferometric procedures using the phase of the satellite-transmitted carrier signals measured at the same instant at two or more antennas.

4.4.1 Fixed Antennas

Three points, not in a straight line, define the orientation of a plane with respect to a given coordinate system. If a vehicle is attached to this plane, then the vehicle orientation is also determined. The Global Positioning System of satellites defines a coordinate system which can be related to the fixed earth. The GPS satellites also provide coded signals which can be received, decoded, and processed with a suitable algorithm to establish the location of the receiver antenna, with respect to this coordinate system, at a specific time. Repeated processing of the received GPS signals will produce a three-dimensional track of the vehicle's position with respect to time. This information can then be used to navigate the vehicle. In a similar fashion, the three-axis orientation of a vehicle can be computed if signals are available simultaneously from three or more antennas.

In order to do three-axis orientation, the three antenna positions must be known relative to each other in the vehicle reference frame. Then, comparison of the phase of the GPS signals received at the several antennas allows one to orient the plane containing the antennas with respect to the GPS coordinate system. This in turn orients the vehicle in the same system.

Simultaneous three-dimensional navigation and three-axis orientation are possible if a suitable receiver and reduction algorithm are mated. The time multiplexed receiver goes a long way towards meeting the receiver requirement of tracking four satellites (for instantaneous navigation) simultaneously from three antennas (for instantaneous orientation). The system uses software to multiplex the received signals among the several software tracking loops. These loops operate independently on an assigned satellite signal and frequency (L1 or L2).

The receiver has a fundamental clocking interval of 20ms(T). All receiver operations are some integer fraction or multiple of T. Typically, the receiver dwells for T/2 on each satellite and T/4 on each frequency of a particular satellite. Thus, it has completed an observation cycle appropriate for the navigation function using a single antenna (two frequencies and four satellites) after 2T. Collecting data to solve the orientation problem requires that an RF switch be inserted between the antennas and the receiver. This switch would be activated in synchronization with the receiver clocking interval T. Then when the switch is operated, the next antenna would be selected to feed signals to its dedicated software tracking loops. In the time between updates of a particular tracking loop, it would propagate using the most recent data. Thus, it might be possible to keep several auxiliary sets of tracking loops (one set per antenna) running in the navigation processor, each set being updated by the receiver processor software. Update intervals of these auxiliary trackers would be at intervals of 2NT, where N is the number of antennas being used. The receiver would then provide the data from all of its tracking loops to an external computer. This computer would contain the navigation-orientation algorithm and display the continuously updated solution. Figure 6 illustrates the proposed arrangement.

Navigation accuracies depend upon the precision of the pseudorange measurement, the errors in the satellite ephemeris, and the geometric strength of solution provided by the observed satellites. Receiver pseudorange accuracies using P code tracking are quoted as being less than 1.5 meters (Johnson, et al., 1981-82). Therefore expected three-dimensional positioning should be as good as any conventional code tracking receiver.

Orientation accuracies are proportional to the accuracy of the phase difference measurement (Δl_i), and inversely proportional to the distance between the antennas (b_i) multiplied by the sine of the angle θ_{ij} between the line connecting the antennas and the satellite vector:

$$\Delta \theta_{ij} = \frac{\Delta l_i}{b_i \sin \theta_{ij}} \qquad (4)$$

The subscripts in this equation indicate the particular baseline (i) and satellite (j).

Receiver phase measurement accuracies are expected to be about 0.005 meter. If an optimal four satellites are always contributing data, then the resulting angular precision will not be seriously perturbed should the position of one satellite cause the sin θ_{ij} to approach zero.

Simulations have shown that equation (4) can be used to estimate the angular accuracies that result for a given phase measurement error and baseline length. For example, the standard deviation of the angular estimate, given a 2-meter baseline and a measurement error of 0.005 meters, can approach 3 milliradian (Hermann, in press).

Initial tests of the concepts will begin in 1984 with support and cooperation from the Eastern Space and Missile Test Center, Patrick AFB, Florida. Three GPS geodetic receivers, paired with three antennas, will operate in the conventional navigation mode aboard the USNS Redstone, a scientific survey ship. The three receivers will be synchronized to a single frequency standard and will track the same satellites so that simultaneous phase data are available. This is crucial for a successful test. The broadcast ephemeris, receiver diagnostics, pseudoranges, and phase data will be recorded on tape for postprocessing. Comparison data will be provided by the ship's inertial navigation system. Should the results of the processing show promise, work will begin toward implementing the real-time system.

4.4.2. Rotating Antenna

Instead of phase measurements, an alternate procedure uses change-in-phase measurements. This removes the requirement that the phase measurements be coherent. Also, instead of using three fixed antennas on a platform, the procedure uses one antenna rotated in the plane of the platform. Therefore, no additional signal channels are required of the receiver in order to determine both real-time positioning and orientation for low dynamic vehicles.

This platform orientation procedure takes advantage of two physical characteristics. First, the GPS receiver is designed to track four satellites even when the antenna is attached to a high dynamic vehicle, such as a fast airplane or missile. The proposed procedure is to be used on low dynamic vehicles, such as boats, helicopters, or slow-flying aircraft which support geophysical surveys. Therefore, the antenna will be able to have some additional motion and the receiver will still be able to track four satellites.

Secondly, movement of the antenna away from its location and then back to its original location does not change the phase measurements which would have been taken if the antenna had not moved between measurement times. Here, it may be necessary to deterministically compensate for antenna spin. This is a result of the Doppler effect and assumes that the receiver is tracking satellites during the antenna motion.

The proposed procedure is to periodically change the position of the electrical center of the antenna. The position change is done slowly enough not to lose track on the satellites, but faster than the dynamics of the vehicle. The periodic changes in antenna position imply periodic changes to known positions on the vehicle, which are synchronized in time with receiver measurements.

The procedure is not restricted to a specific type of periodic motion. One of the simplest applications would be periodic circular motion in the plane of the platform. This would be accomplished by placing an antenna at the end of a rotating arm, or within a rotating disk. The antenna may require a coupler for connection to the receiver cable. The accuracy of such a device would depend on a number of factors. Most important are the radius of the circular motion, the change-in-phase measurement accuracy, the vehicle dynamics, the rotational rate, rotational positioning accuracy and the clock accuracy. Many other types of configurations are possible, and the change in position of the antenna's electrical center could also be accomplished electronically rather than mechanically.

The orientation estimation is, of course, made at discrete times. In a dynamic situation, the vehicle and the antenna move between measurements. Consequently, an interpolation procedure is necessary to estimate the measured values at the appropriate times.

A static demonstration of GPS attitude determining capabilities has been performed. Here, available data (Evans, et al.,1981) from a Stanford Telecommunications, Inc. (STI) geodetic GPS receiver were used. The antenna was periodically moved to three locations of a platform. The position changes were every 15 minutes and done within a 60-second change-in-phase measurement interval. Since the receiver tracks only one satellite at a time, data from repeated position changes were used to emulate tracking multiple satellites during the tracking interval.

The change-in-phase measurements are used to obtain observed values of change in range. This is done by integrating the received frequency $f_r(t)$, subtracted from a precise ground station frequency f_g, over a time interval $(T_{i-1}, {}_i)$. The received frequency is the sum of the transmitted frequency f_T and the Doppler effect. Therefore, the change in phase, in cycles, is

$$= {}^{ti}, f_g - f_r(t).dt \qquad (5)$$

$$= {}^{ti}_{ti-1}, f_g - f_r + f_r \frac{R(t).\ dt}{c} \qquad (6)$$

$$= {}^{ti}, f_g - f_t)(t_i - t_{i-1}) + \frac{ft}{\ }, R(t_i) - R(t_{i-1}). \qquad (7)$$

where c is the speed of light and R(t) is the range at time t to the satellite. The measured change in phase is used to determine the observed change in range using equation (7). Using the change-in-range values from the two-frequency GPS channels, a first-order ionospheric correction is made. Next, the calculated ranges from the assumed position are fit to the data to determine biased ranges and improvements to six orbit elements and tropospheric refraction corrections. The difference in the residuals of these fits at times before and after the antenna moves represents the observed change in range due to the position changes. The details of this method have been presented previously (Evans, et al., 1981).

Thus a procedure is proposed to determine platform orientation using the Global Positioning System and a multiple satellite tracking receiver using change-in-phase measurements from an antenna whose electrical center is periodically moved within a plane. In order to demonstrate the procedure further, available change-in-phase measurements from an antenna moving in a stationary plane are required.

The root-mean-square error of the demonstrated angular estimates was less than half a degree for the 2-meter baseline. This is a reasonably good result considering the long time interval of the position changes, and it approaches the accuracy of the survey procedures for determining the truth directions.

The accuracy of the ionospheric-corrected, phase-differenced measurements is about 2 centimeters for the receiver used in the test (Johnson, et al., 1981-82). The addition of a similar value for the clock error over the 60-second measurement interval (Evans, et al., 1981) increased the range difference measurements to a little less than 3 centimeters. For a 2-meter baseline, this translated to a single dimension orientation estimation accuracy of about 14 milliradians, or 0.8 degree. This expected accuracy is in agreement with the results of the test case.

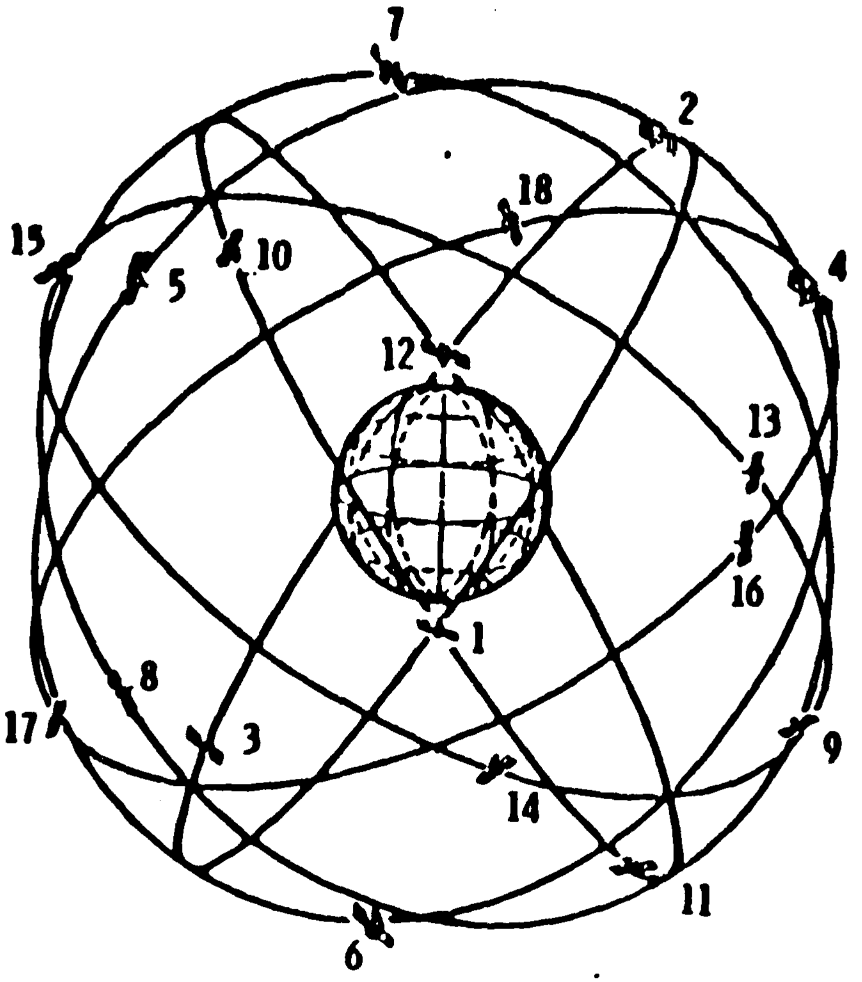
For 2-meter or smaller baselines using the GPS receiver, the rotating antenna procedure should be slightly less accurate than the fixed antenna procedure. Here, the clock error must be kept well below the phase measurement accuracy of the receiver. This, of course, depends on the clock accuracy and the rotational time interval. Using the expected one-degree L_1 channel phase measurement accuracy (Johnson, et al., 1981-82), results in a range difference accuracy of about 0.025 centimeter. This expected range-difference measurement accuracy is directly related to the orientation estimation accuracy and represents an improvement by a factor of about 27 over the test case accuracy. A rotational period of one second would result in a clock error, for a reasonably priced oscillator (Standard Product Price Book, 1982) of one part in 10^{12} over one second, or .0103 centimeter. It is felt that additional contributing errors such as the change in orbit error during the one-second rotation and mechanical positioning errors should be minimal. Also, interpolation errors for low dynamic vehicles should be small. It will be necessary to compensate for electrical phase center movement within the antenna. However, with one antenna, phase center biases are eliminated. In summary, if the expected phase measurement accuracies of the new multiplexing GPS geodetic receiver are as expected, then the orientation estimation accuracies for a 1-second rotation period will be significantly improved over the presented test case and should be comparable to, although slightly less accurate than, the fixed-antenna procedure for small baselines.

The test case demonstrates that in addition to position and velocity determination, the NAVSTAR Global Positioning System can be used for orientation determination. The accuracy analysis indicates that GPS orientation determination can be utilized in a wide range of applications.

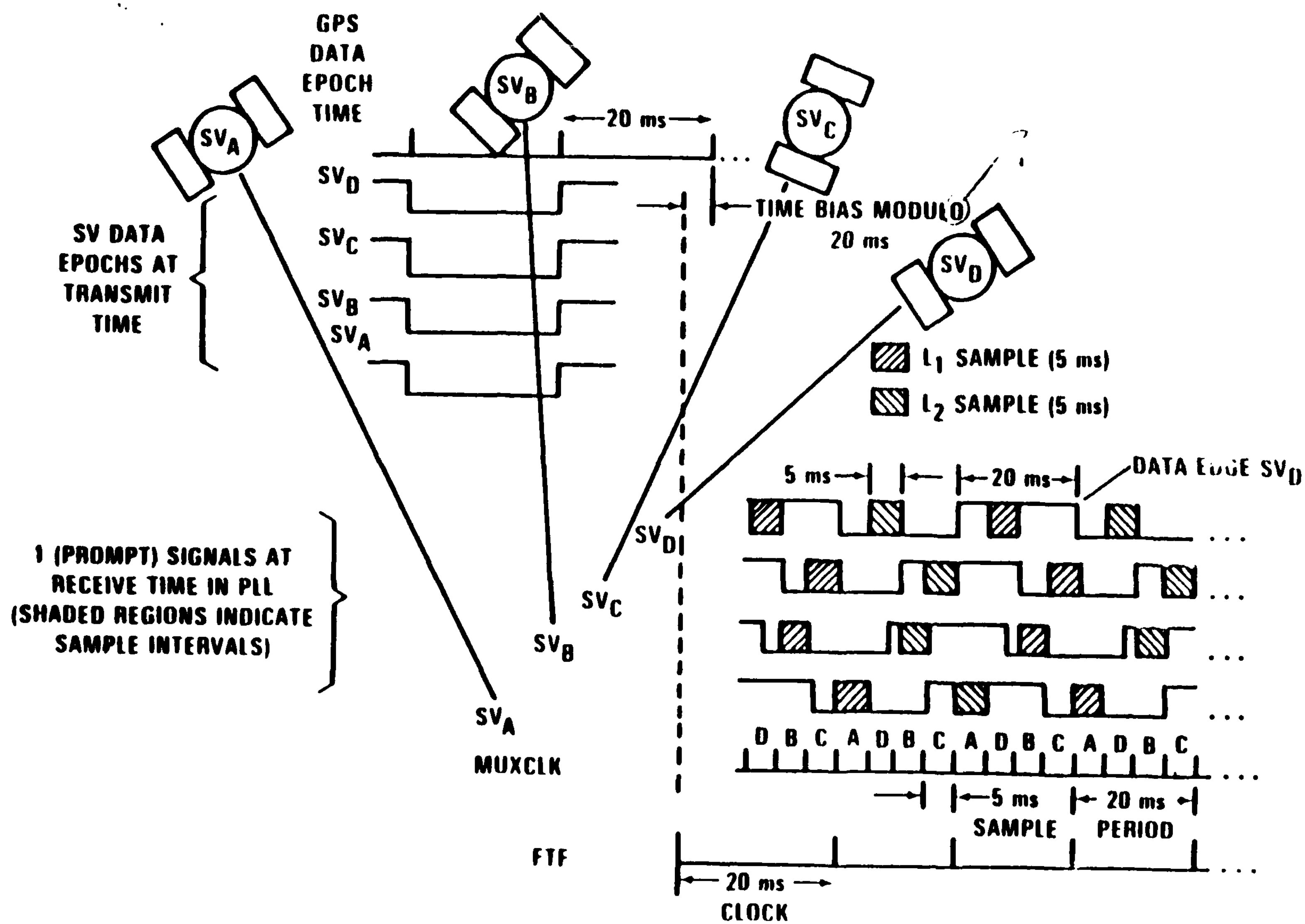
5. CONCLUSION

Currently an exhaustive test program is underway to assess the accuracies of the approaches discussed above which support geodetic positioning, platform orientation, and navigation support to geophysical surveys. Other applications such as global time transfer using alternate instrumentation are under development. The projected accuracy of GPS satellite time and position estimates and availability will foster new ideas on applications, and as these ideas are germinated, user equipment technology will follow.

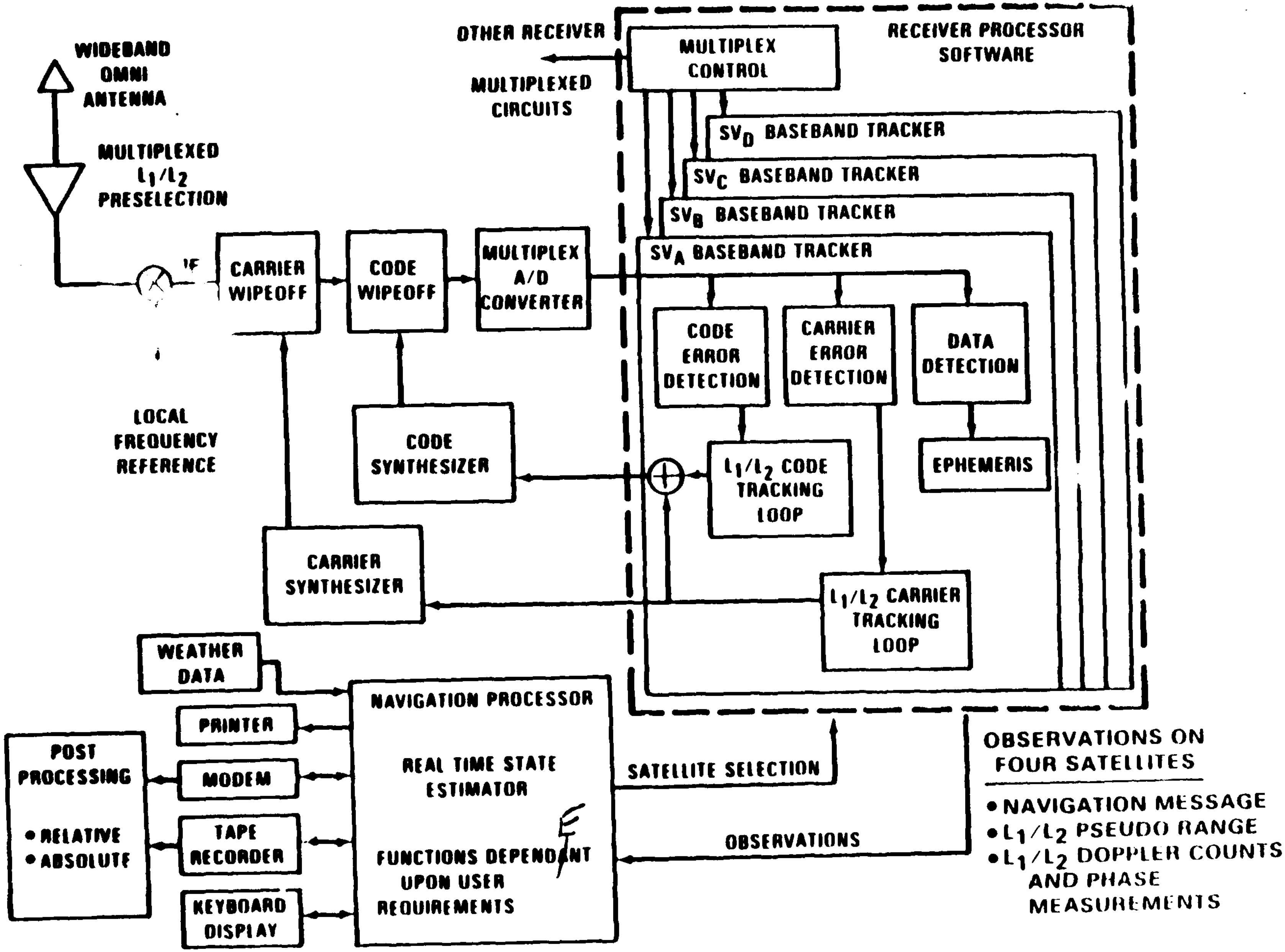
The Navstar GPS 6-Plane, 18-Satellite Configuration



MULTIPLEX TIMING



Figure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CODE SYNTHESIZER
CARRIER SYNTHESIZER
OTHER RECEIVER
MULTIPLEXED CIRCUITS
MULTIPLEX CONTROL
RECEIVER PROCESSOR SOFTWARE
SV_D BASEBAND TRACKER
SV_C BASEBAND TRACKER
SV_B BASEBAND TRACKER
SV_A BASEBAND TRACKER
CODE ERROR DETECTION
CARRIER ERROR DETECTION
DATA DETECTION
L_1/L_2 CODE TRACKING LOOP
EPHEMERIS
L_1/L_2 CARRIER TRACKING LOOP
WEATHER DATA
PRINTER
MODEM
TAPE RECORDER
KEYBOARD DISPLAY
POST PROCESSING
• RELATIVE
• ABSOLUTE
NAVIGATION PROCESSOR
REAL TIME STATE ESTIMATOR
FUNCTIONS DEPENDANT UPON USER REQUIREMENTS
SATELLITE SELECTION
OBSERVATIONS
OBSERVATIONS ON FOUR SATELLITES
• NAVIGATION MESSAGE
• L_1/L_2 PSEUDO RANGE
• L_1/L_2 DOPPLER COUNTS AND PHASE MEASUREMENTS

Figure

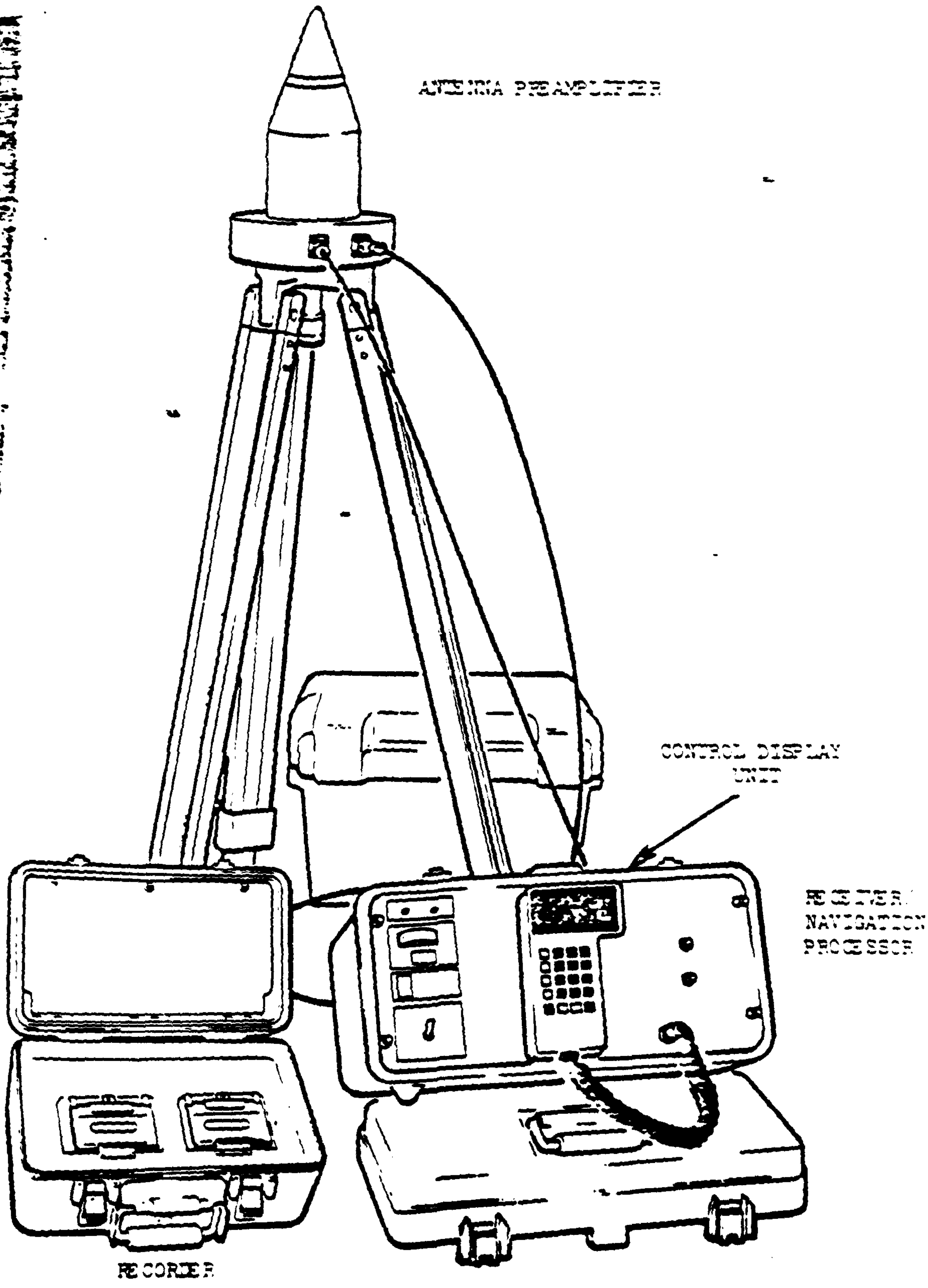

FIGURE -

BASIC GEOSTAR GPS SURVEY RECEIVER

DYNAMIC RELATIVE POSITIONING

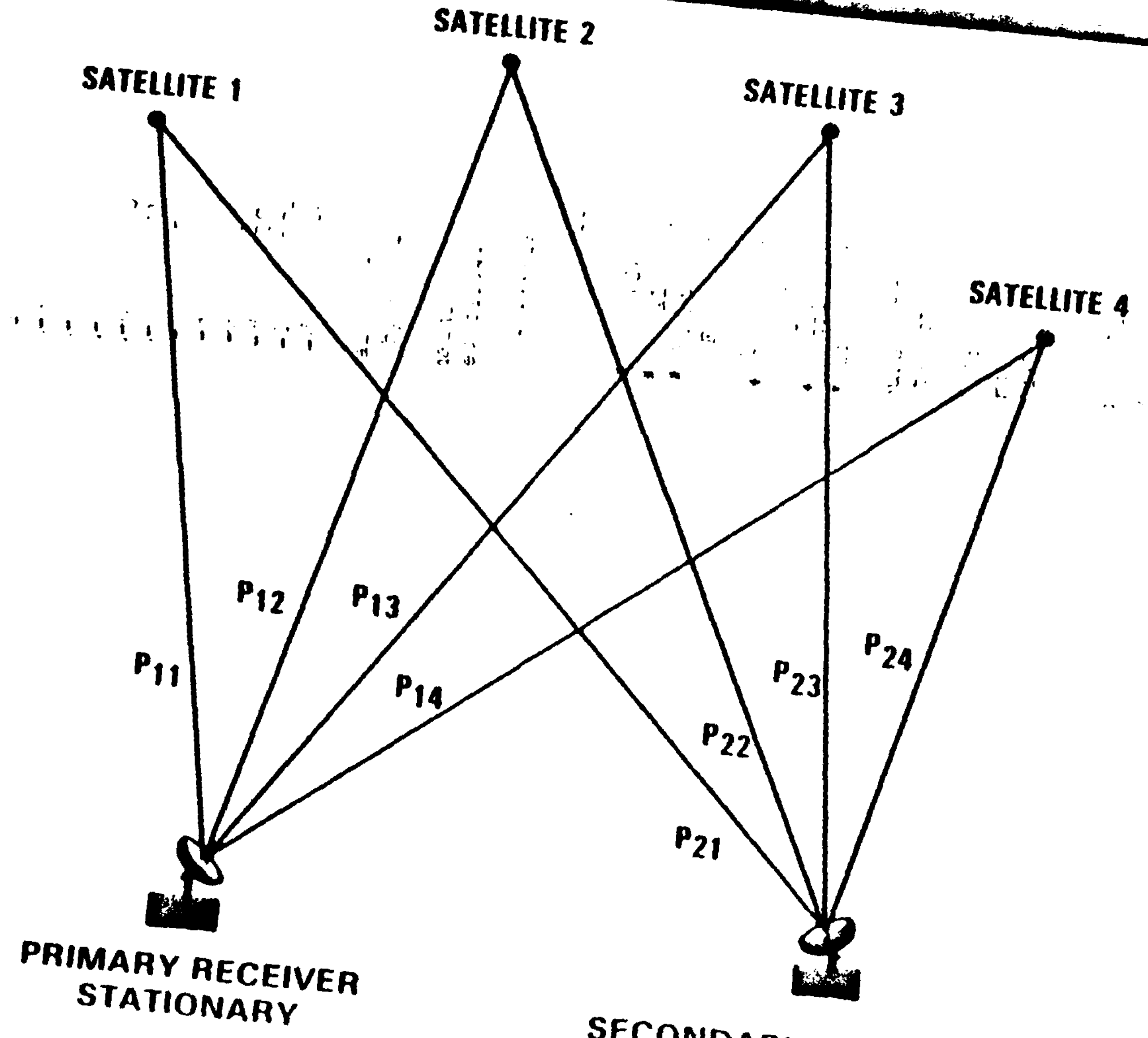

Figure 5

ADAPTATION OF GEOSTAR FOR MULTIPLE ANTENNA OPERATION

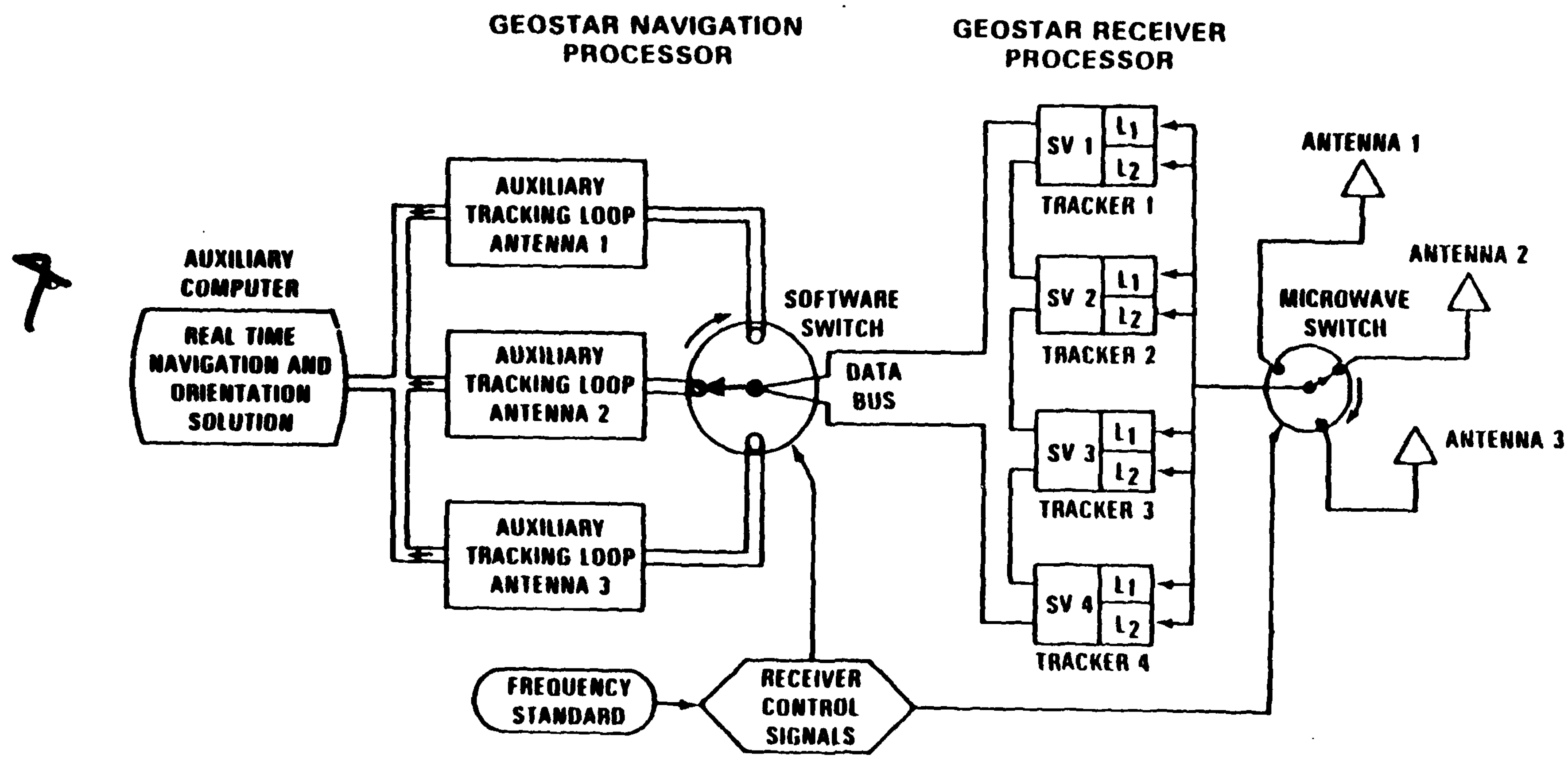

Figure 6

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